Temperature and Field Dependence of the Energy Gap of MgB_2/Pb planar junction

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We have constructed MgB_2/Pb planar junctions for both temperature and field dependence studies. Our results show that the small gap is a true bulk property of MgB_2 superconductor, not due to surface effects. The temperature dependence of the energy gap manifests a nearly BCS-like behavior. Analysis of the effect of magnetic field on junctions suggests that the energy gap of MgB_2 depends non-linearly on the magnetic field. Moreover, MgB_2 has an upper critical field of 15 T, in agreement with some reported H_{c2} from transport measurements.

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I. INTRODUCTION

Recently Nagamatsu et al.[1] has discovered superconductivity in the commonly available compound MgB_2 with a T_c of 40 K. Similar to the cuprates, MgB_2 has a layer structure and hence many of its superconducting properties may show anisotropic effect. For instance, the anisotropy ratio $\gamma = \xi_{ab}/\xi_c$ has a reported value that varies from 1.1 to 9.0[2,3]. There is also evidence that the energy gap value is very different along these two directions showing anisotropic s-wave or two-gap behavior[4−9]. On the other hand, as clearly demonstrated by isotope effect[10,11] and neutron scattering[12,13], MgB_2 is different from the cuprates and its Cooper pairs are phonon mediated.

Although the pairing mechanism in MgB_2 is thought to be phonon mediated, there are still many experimental results that lack appropriate explanation. Many of these unanswered problems may lead to unexpected and interesting physics of superconductivity. For example, there is no consensus about the magnitude of the energy gap until now. Many techniques have been used to measure the gap such as Raman spectroscopy[14,15], far-infrared transmission[16−18], specific heat[19−21], high-resolution photoemission[22] and tunneling[4−9,23−28]. Most tunneling data on MgB_2, as in the case of many other newly discovered superconductors, are obtained from mechanical junctions like scanning tunneling microscope[5,6,8,23−25], point contact[7,9,26−28] and tunneling junctions[4].

It is critical to determine whether the small gap value reported by many groups[23] is a real bulk property or a result of surface degradation. One direct method is to measure the temperature dependence of the energy gap. Since the structure of a mechanical junction will change as the temperature is varied or an external field is applied, it is not stable enough to study temperature dependence of the energy gap. The situation will be worse if the sample is not homogeneous and the gap value varies with the probe position. The more reliable measurement for temperature dependence of the energy gap is from sandwich type planar junctions where any variation in the tunneling spectra will be a pure result of the sample under study not due to any structural changes in the junction. To our best knowledge, in this paper we report the first energy gap temperature and magnetic field dependence of MgB_2 by planar junctions.

II. EXPERIMENTAL DETAILS

MgB_2 sample is prepared by reacting Mg turnings (99.98%) and boron powder (99.99%, -325 mesh) with the stoichiometric composition 1:2 respectively. Magnesium and boron are mechanically pressed and sealed in a tantulum tube (99.9%, 2.4 mm inner diameter). The tantalum tube is then sealed inside a quartz tube and placed inside a box furnace at 950 °C. It is then quenched to room temperature after two hours. The polycrystalline MgB_2 is then characterized using X-ray diffraction, resistivity and dc SQUID magnetometer (Quantum Design MPMS) measurements.

Junctions are constructed by attaching two leads to MgB_2 sample and molding it inside epoxy resin. It is then ground to expose the sample and mechanically polished to a smoothness of 0.3 micron. Pb, a superconductor with $T_c \approx 7.2$ K and $H_c(0) \approx 0.08$ T, is evaporated on the top as a counter electrode. We used Pb to sharpen the peak features and also as a control to monitor the tunneling conditions. In this paper we will limit our analysis only to the data when Pb is normal, which is simpler to understand. We have also attempted to grow artificial barrier by sandwiching a thin oxidized aluminum layer between the sample and Pb electrode. This will in general lead to very large junction resistance, even with the minimal thickness of aluminum layer. So far, the best junctions are still from those with natural barrier. The junctions show stability against any temperature changes in the full range from 4.2 K to room temperature, but can survive only up to a magnetic field (perpendicular to the barrier) of approximately 3.2 T.

III. RESULTS AND DISCUSSIONS

X-ray diffraction pattern shows no trace of other phases in the sample. Both resistivity and SQUID mea-

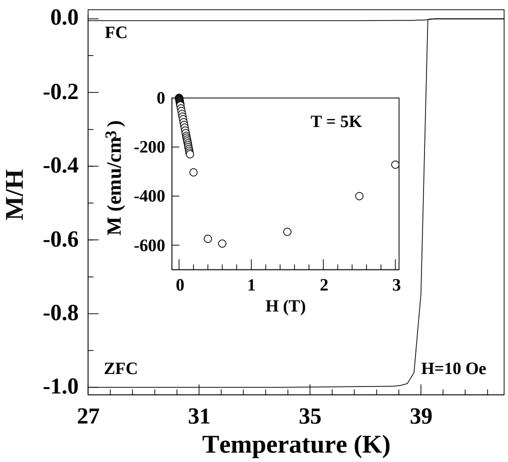

FIG. 1: Magnetization divided by an applied filed of 10 Oe as a function of temperature for both Zero Field Cooled (ZFC) and Field Cooled (FC) modes. The inset shows the magnetization curve $M(H)$ measured at $T = 5$K. For clarity, the x-axis (inset) is limited to small values of H.

surements have determined the T_c^{onset} to be 39.5 K (defined by 2% criteria) with a sharp transition width of 0.7 K (10%-90% criteria). Fig. 1 (main panel) shows the temperature dependence of susceptibility for both zero-field cooled (ZFC) and field cooled (FC) modes. Taking in account the demagnetizing factor of the measured cylindrical sample with $\gamma = 1$ (ratio of length to diameter), the sample shows a perfect diamagnetic shielding $M/H = -1$. This result along with a Residual Resistance Ratio $RRR = R(300)/R(T_c) = 8$ reflects both the sample's good quality and grains coupling. The small FC susceptibility signal observed here is a common feature for such polycrystalline MgB_2 samples sintered around 950 °C or higher[29,30]. This can be attributed to large trapping of flux by cracks and voids that reflects also the good coupling of grains[31]. It is interesting that the lower critical field $H_{c1}(5K) = 0.2$ T as estimated from the magnetization curve (Fig. 1, inset). This value is significantly larger than those reported by other research groups[29,32] and can be attributed to the good quality of the sample.

The inset of Fig. 2 shows how the conductance curves evolve with temperatures below lead T_c. For this S/I/S junction we can roughly estimate the energy gap of MgB_2. It is clear that the spectra are sharpened significantly as the Pb gap Δ_{Pb} opens up. Since $\Delta_{Pb}(0)$ is about 1.2 meV and the peak position of the 4.2K curve is at 3.2 meV which can be considered as the half sum of gaps, we can estimate Δ_{MgB_2} to be about 2 meV. The corresponding value of $2\Delta/kT_c$ is only about 1.18, much smaller than the BCS value of weak coupling superconductors. This is consistent with other small gap results from tunneling measurements[23]. As can be seen from Fig. 2 (main panel), the smaller peak around 9 meV survives for temperatures up to 21.16 K. Similar features are

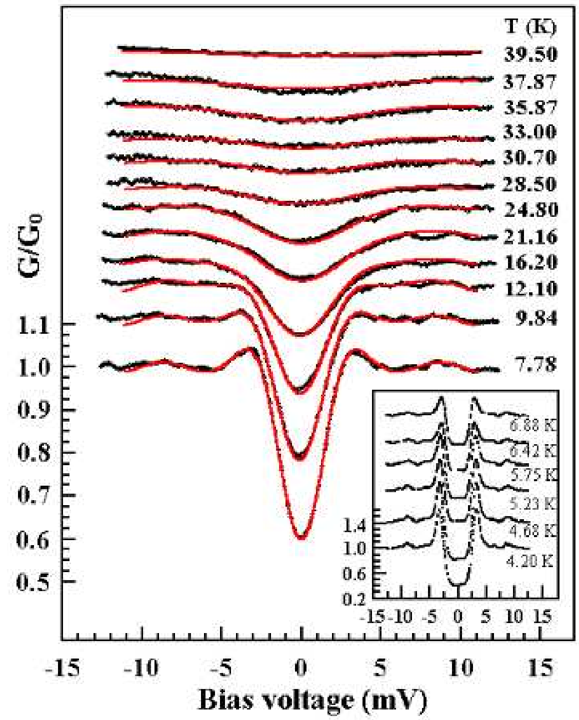

FIG. 2: Temperature dependence of the experimental tunneling conductance spectra normalized by the conductance at 15 mV (dots). The spectra at temperatures above T_c of lead are represented in the main panel with the corresponding two-gap BTK fittings (red lines). For clarity the curves are vertically shifted.

commonly found in other tunneling data[6].

It is intriguing to find this very small energy gap in a high T_c superconductor like MgB_2. All tunneling data published so far can be summarized into three main categories, according to the interpretation: one-gap[23−26,28], two-gap[4,6−9] and gap anisotropy[5]. If there is only one single gap, then it is likely that the small value is a result of surface degradation. However, our data do not support this explanation because the gap exists up to the bulk T_c. So far, there is no direct observation of two distinguished gaps in the same tunneling spectrum. Mostly a small feature at a higher energy is interpreted as the second gap[7]. This two-gap approach is in accordance with the 2D and 3D Fermi surfaces proposed by Liu et al.[33]. On the other hand, Chen et al.[5] proposed an anisotropic s-wave pairing model with $\Delta_{xy} = 5$ meV and $\Delta_z = 8$ meV to best fit their tunneling curves.

We have used Blonder, Tinkham, and Klapwijk[34] (BTK) model to analyze the curves when Pb is normal (Fig. 2, main panel). In this model, in addition to quasiparticle tunneling, the possibility of Andreev reflection and normal reflection by the barrier is also included. As indicated by our fitting, the barrier strength Z of our junction is not strong enough to prevent Andreev reflection from happening. A depairing term Γ is also included because of shortening in quasiparticle lifetime by differ-

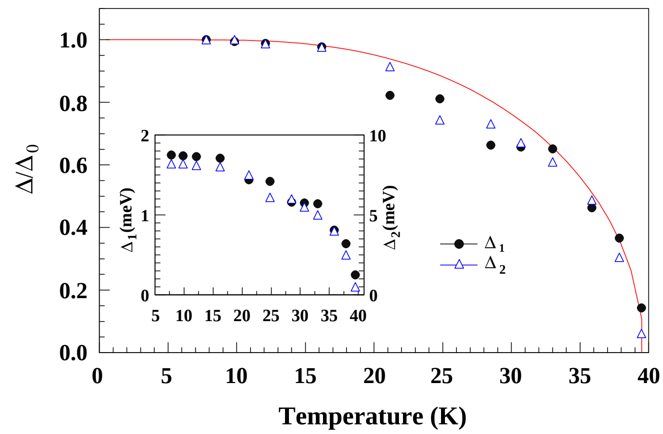

FIG. 3: Temperature dependence of the two gaps Δ_1 and Δ_2 normalized by their values at $T = 7.78$ K. The absolute values are shown in the inset. The solid line represents the expected BCS $\Delta(T)/\Delta(0)$ with $T_c = 39.5$ K.

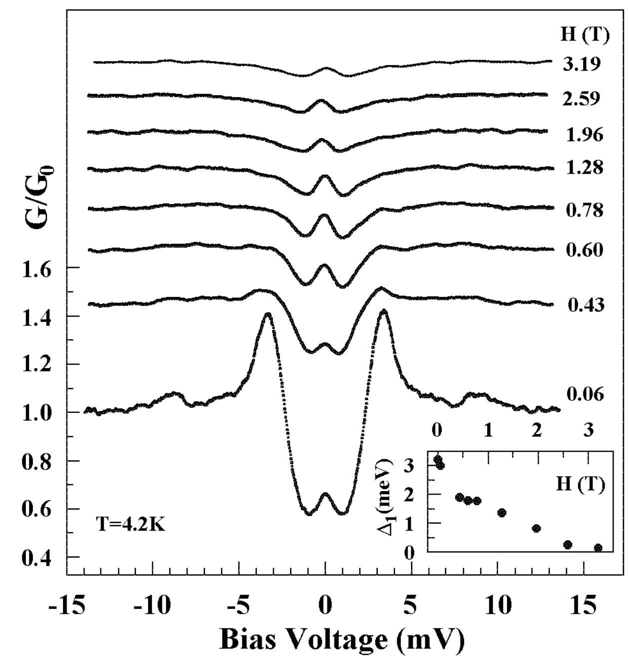

FIG. 4: Magnetic field dependence of the experimental tunneling conductance spectra normalized by the conductance at 15 V. The inset shows the field dependence of Δ_1 measured at 4.2 K.

ent scattering processes.

Here we have assumed the two-gap model to cover also the small feature around 9 meV (Fig. 2, main panel). We consider this feature as the second energy gap Δ_2 in MgB_2. Also, the two gaps contribute to tunneling independently. Therefore, we assign a small percentage of tunneling C_2 for Δ_2 and $C_1 = 1 - C_2$ for the smaller gap Δ_1. The parameters Γ, Z, Δ_1, Δ_2, C_1 and C_2 are used to best fit the curve at 7.78 K and their values are 0.95 meV, 1.33, 1.75 meV, 8.2 meV, 0.94 and 0.06, respectively. All these parameters except the Δ's are kept constant for all higher temperature curves, i.e., the Δ's are the only adjusting parameters. From the quality of the fittings, it is justifiable to say that Γ, Z and C's are independent of energy and temperature within the ranges of our measurement. Furthermore, the zero bias offset is purely a result of Andreev reflection at the barrier.

The inset of Fig. 3 shows the temperature dependence of the two gaps. The main panel shows both gaps normalized to their values at $T = 7.78$ K along with the BCS expected behavior (solid line). As can be seen, both Δ_1 and Δ_2 survive to T_c of bulk MgB_2 with a small deviation from BCS as we try to apply the two-gap model. Since the tunneling features are mainly due to Δ_1 ($C_1 = 0.94$) and they survive up to T_c of MgB_2, it is justifiable to consider Δ_1 as a true bulk property of this superconductor. This two-gap fitting gives $\Delta_2(0)/\Delta_1(0) \approx 4.5$, close to both the theoretically predicted[33] and experimentally suggested[19] value. Nevertheless, there are still unexplained problems with this two-gap model. For example, why the large gap contributes that little to tunneling, $C_2 = 0.06$, for such a polycrystalline sample? Our analysis above still holds for a single gap superconductor by setting $C_2 = 0$, but then we have to explain why Δ_1 is so small.

To further characterize the junctions, we have also studied the field dependence of the tunneling spectra at 4.2 K (Fig. 4, main panel). The junction in an external field normal to the barrier is not as stable as its performance against temperature changes. It experiences slight changes even when a small field is applied. This can be seen from the development of the zero bias conductance peak, similar to that observed by another group[26]. This can be explained by enhancement of micro-shorts through the barrier as a result of the applied field. Furthermore, most junctions collapse and the tunneling spectra transit from quasiparticle to Josephson tunneling at fields of about 3.2 T. In this paper, we focus only on quasiparticle tunneling spectra. It can be seen from Fig. 4 (main panel) that the quality of the spectra has severely degraded when H exceeded H_c of lead. The curve at 0.43 T is more severely smeared and depressed as compared to the curve at $T = 7.78$ K (Fig. 2). This reflects the fact that this field is already greater than H_c of Pb. Using the peak position of the small gap Δ_1, we can roughly estimate its dependence on H as shown on Fig. 4 (inset). It is worth noting that $\Delta_1(0T) - \Delta_1(0.43T) > \Delta_{Pb}$. This supports the above argument on the condition of the curve at 0.43 T. Moreover, the energy gap depends non-linearly on the the magnetic field. Further work should be done to investigate this dependence.

Since MgB_2 is a type II superconductor, the effect of magnetic field is to produce vortices and hence the order parameter on the surface is not homogeneous anymore. In a simple model, the tunneling spectrum is an ensemble of all different gap values sampled within the junc-

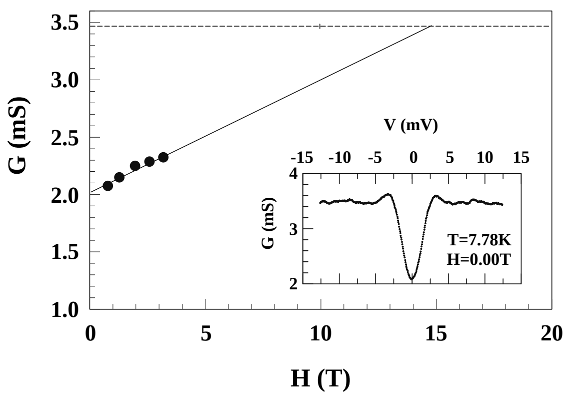

FIG. 5: Magnetic field dependence of the minimum conductance. The linear fit intersects the normal conductance line in a point corresponding to $H_{c2} \approx 15$ T. The intersection with the vertical axis matches the minimum conductance offset of the spectrum at 7.78 K and 0 T (inset).

tion area (0.05 mm^2). If we consider the vortex core as a normal region, and the number of vortices produced is proportional to the applied normal field, then the zero bias conductance should be proportional to that field[35]. To study this dependence, we have fitted our tunneling spectra within the gap by parabola to remove the zero conductance peak. The zero conductance can then be estimated from the parabola. In Fig. 5 (main panel) we have plotted the zero bias conductance versus the external applied field. It is clear that the zero bias offset increases linearly with the external field. By extrapolation to the normal conductance, we can estimate H_{c2} of MgB_2 to be about 15 T. This value is in agreement with H_{c2} of bulk MgB_2 from transport measurements (see, e.g., Ref. 29, 36) rather than the small reported value of about 6 T from tunneling analysis (see, e.g., Ref. 24). From Fig. 5 we can also estimate the S/I/N zero bias offset at zero field to be around 2.1 mS. This agrees with the zero bias offset in the zero field conductance curve at 7.78 K (Fig. 5, inset).

IV. CONCLUSION

We have prepared MgB_2/Pb planar junctions to study the temperature and field dependence of the energy gap of MgB_2. The temperature dependence data indicate that the small energy gap we have measured is indeed a bulk property of MgB_2. Moreover, our data do not contradict the two-gap scenario by considering our reported gap of about 2.0 meV as the small gap. Analysis of the effect of magnetic field on the junctions shows that MgB_2 has an upper critical field of about 15 T which is consistent with most transport measurements of H_{c2}. Moreover, the energy gap shows a non-linear dependence on the magnetic field applied perpendicular to the barrier.

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